

A Hitchhikers Guide to the Black Arts (of Earth system modelling)

Assessment 2

Write-up of this exercise will constitute: **80% of the total unit marks for GEOGM1110**

100% of the total unit marks for GEOGM1404

Hand-in date is: **Thursday 24th January (Week 12) (both courses)**

***** Running the model experiments and the write-up must be done *individually*. *****

For the format – follow the ‘manuscript preparation and submission’ guide for Nature:

<http://www.nature.com/nature/authors/gta/index.html#a1>

For **GEOGM1110**: use the instructions for writing a Nature ‘Article’, e.g.:

- <3000 words for the main text
- no more than 5-6 Figures (and Tables)
- a brief model description should be included in a ‘Methods’ section (see Nature guidelines)

For **GEOGM1404**: use the instructions for writing a Nature ‘Letter’, e.g.:

- <1500 words for the main text
- no more than 3-4 Figures (and Tables)
- a brief model description should be included in a ‘Methods’ section (see Nature guidelines)

If you would like to show additional model plots and/or description that is not central to the conclusions of your paper – you can include a separate section of ‘Supplementary Information’:

<http://www.nature.com/nature/authors/submissions/final/suppinfo.html>

You do not have to number the references: writing them out as e.g. ‘*Watson et al.* [2000]’ in the main text is fine. Nor are you expected to produce a layout that looks like a published paper.

The assignment is to assess whether ocean carbon geoengineering is an effective means for reducing future ocean acidification and marine ecological impacts.

To do this, you will first need to assess what the expected future acidification of the ocean is, particularly in the context of organisms and/or ecosystems that may be at ‘risk’. It is your choice as to whether to focus on particular organism/region and/or a specific carbonate parameter, or provide a more wide-ranging summary assessment of impacts. A reference SRES CO₂ emissions scenario (‘A2’) is provided for you, but you do not have to stick with this particular one – testing and comparing multiple scenarios would be an alternative approach.

Three different possible ocean carbon geoengineering (more generally known as ‘carbon dioxide removal’ geoengineering – ‘CDR’) scenarios are provided (see A.5). It is up to you whether you concentrate on one particular one, test them all, some combination of them, or something else entirely. You might also relate geoengineering effectiveness with a low emissions (mitigation) scenario. Optionally: some assessment and discussion of the ‘feasibility’ (practical, economic) as well as legal and/or social issues may well form part of your assessment, but should not constitute more than about ~500 words of the paper.

Remember to provide some sort of assessment, even if mostly regulated to ‘Methods’ or even in Supplementary Information, as to whether the model makes credible projections of carbon uptake and ocean acidification in the first place, and in what respects your results should be treated with caution.

A.0 Remember: you will be working individually.

Although your previous cGENIE modeling and experimentation may well inform your work for the assessed exercise, you are using a different computer and model configurations and you cannot make direct use (i.e. copy over *restart* files) of your previous model experiments (which in any case were done jointly and only on one person's account).

This is only Part 'a' of the full instructions for the assessed exercise. You have already been given the outline (sufficient for starting background reading). This handout details how to set up the basic experiments. The next (Part 'b') handout will contain the explicit goals and geoengineering experiment possibilities. This will follow shortly.

A.1 The (new) cluster you will be logging into and using is:

`marble.ggy.bris.ac.uk`

Your individual usernames and password are the same as before.

If you would like to change your password, once you are logged in just type:

```
$ passwd
```

and follow the on-screen instructions. (Should you forget it I can reset it.)

Install the cGENIE model (including carrying out the 'test' just to be sure) as per the instructions given in Section 1 of the 1st Lab handout.

A.2 For all your experiments, you will need a (long) preindustrial *restart* (spin-up), which you will have to create for yourself (remember that a *restart* is simply a normal experiment that you use for a starting point for further experiments). The preindustrial experiment, should you choose to run it for e.g. 10,000 years, would be run as follows:

```
$ ./runcgenie.sh cgenie_eb_go_gs_ac_bg.worjh2.BASEFe LABS expx0_SPIN 10000
```

(you may want to explore whether 10,000 years is too long or too short).

Note that the *user-config* used here (`cgenie_eb_go_gs_ac_bg.worjh2.BASEFe`) differs from previous work (although you will not have to change it again).

There is a slight modification to the command to submit jobs to the queue:

```
$ qsub -j y -o cgenie_output -V -S /bin/bash runcgenie.sh  
cgenie_eb_go_gs_ac_bg.worjh2.BASEFe LABS expx0_SPIN 10000
```

(i.e. you drop the (cat) 'queue' specification).

A.3 You have also been provided with an example *user-config* for running the historical transient: `expx1_HIST`, which of course will use the preindustrial spin-up experiment (`expx0_SPIN`) as its *restart*. There is also an example future fossil fuel CO₂ emissions scenario provided:

`expx2_FUTURE`, which assumes an 'A2' emissions scenario, with further emissions past year 2100 to create a total fossil fuel CO₂ 'burn' – the area under the curve of emissions (PgC yr⁻¹) vs. time (yr) – 2180 PgC. This emission scenario is specified by the forcing specific parameter:

`bg_par_forcing_name` and its default setting of:

```
"worjh2_FeMahowald2006_FpCO2_Fp13CO2_A2_02180PgC".
```

As per previously, the scaling parameter converts the PgC yr⁻¹ units in the forcing file to mol yr⁻¹ expected by cGENIE.

Embarrassingly ... I cannot remember whether the '2180 PgC' figure is just the total emissions from 2010 onwards, or also includes historical emissions. You should calculate for yourself the area under the curve of emissions rate vs. time to be sure what the total emitted is. (Or, you might run the experiment and calculate the difference between ocean and atmospheric CO₂ reservoirs between 2010 and the end of a future experiment.)

A.4 A template 'A2' emissions *user-config*: `exp3_GEO` is provided. (If you cannot see it in the `LABS` folder, you might have installed `cGENIE` on your 'marble' cluster account before the files were updated. You will then need to change directory to `cgenie` and do an `svn update` before returning to `genie-main` (just as you have done previously).)

`exp3_GEO` includes the parameters for controlling 3 different possible ocean carbon geoengineering schemes, described below. By default, these are commented out and only the forcing for the A2 emissions scenario (`worjh2_FeMahowald2006_FpCO2_Fp13CO2_A2_02180PgC`) with no geoengineering *forcing* is set (parameter: `bg_par_forcing_name`), which you might regard as a control for any with-geoengineering experiments. To activate any particular geoengineering *forcing*: simply comment out the appropriate pair of lines (the first line being the *forcing* specification, and the second one the total flux *forcing* used in the geoengineering scheme). Remember that if you have multiple (un-commented-out) settings of a parameter (e.g. `bg_par_forcing_name`) the value specified in the last occurrence is the one that is applied.

A.5 Each of the example geoengineering scenarios are delineated by a specific *forcing*, constituting a set of files in a uniquely named sub-directory within `genie-forcings`. They are:

- `worjh2_FeMahowald2006_FpCO2_Fp13CO2_A2_02180PgC_FFe`
- `worjh2_FeMahowald2006_FpCO2_Fp13CO2_A2_02180PgC_FPO4`
- `worjh2_FeMahowald2006_FpCO2_Fp13CO2_A2_02180PgC_FALK`

Each *forcing* includes the A2 CO₂ emissions scenario, with the annual emissions (CO₂ flux) `biogem_force_flux_atm_pCO2_sig.dat` in units of PgC yr⁻¹ (== GtC yr⁻¹), hence requiring a units conversion setting in the *user-config* (`bg_par_atm_force_scale_val_3=8.3333e+013`) that is provided for you. (You can completely ignore the carbon isotope settings.)

Each *forcing* also includes a prescribed dust flux to the ocean surface. This is necessary because the model configuration you are using includes a co-limitation of biological productivity by iron (Fe) in addition to phosphate (PO₄). Files are included for the time-dependent control of the supply of dust (`biogem_force_flux_sed_det_sig.dat`) as well as a prescribed spatial pattern its deposition to the ocean surface (`biogem_force_flux_sed_det_SUR.dat`). You do not need to edit these files. For the role of iron in controlling ocean productivity: possible starting points for background reading are: *Ridgwell and Kohfeld [2007]* (PDF available from my website) or *Jickells et al. [2005]* (*Science*).

The details of the 3 different example geoengineering scenarios provided to you are:

- **Iron fertilization** (`worjh2_FeMahowald2006_FpCO2_Fp13CO2_A2_02180PgC_FFe`)

A constant (with time) flux of dissolved Fe (in addition to whatever Fe dissolves into the surface ocean from the dust flux) is specified in: `biogem_force_flux_ocn_Fe_sig.dat`. The magnitude of the applied flux is then scaled in the *user-config* file by the setting: `bg_par_ocn_force_scale_val_9=1.0e+09`

Note that this is simply an example total global flux. You may consider higher or lower fluxes, as well as potentially how 'practical' the annual production and supply of such quantities might be. Contrasting in your paper whatever flux you decide on, with natural Fe fluxes, either globally or regionally, would provide a useful point of comparison for the reader.

A spatial pattern of the flux is also defined, in the file:

`biogem_force_flux_ocn_Fe_SUR.dat`

An example pattern is set (see Section A.6 for details on editing this pattern) – here a row of grid cells at the same latitude in the Southern Ocean. You do not need to retain this pattern. In choosing an alternative: think (and do some background reading) on whether in the modern ocean biological productivity is thought to be at least partly limited by the availability of dissolved Fe. Remember that the model may or may not correspond with reality, i.e. it may or may not predict Fe limitation in the correct regions, which may affect your choice of location for iron fertilization as well as informing your discussion.

There is abundant literature: on the natural Fe cycle in the ocean and Fe limitation of productivity, on experiments carried out to fertilize ocean biota, on model studies of natural

Fe cycling and also some model studies on deliberate Fe fertilization (plus papers on feasibility and ethical considerations).

- **Phosphate fertilization** (worjh2_FeMahowald2006_FpCO2_Fp13CO2_A2_02180PgC_FPO4) ('macro-nutrient' addition)

A constant (with time) flux of dissolved PO₄ is specified in:

biogem_force_flux_ocn_PO4_sig.dat. The magnitude of the applied flux is then scaled in the *user-config* by the setting:

```
bg_par_ocn_force_scale_val_8=2.0e+12
```

Again, you should consider this as an example total flux (i.e. it is not a 'correct' answer!). In choosing a total flux to apply, points of comparison include whatever the total weathering flux (via rivers) of P to the global ocean is. Also: global phosphate (fertilizer) production, which produces an interesting potential conflict between geoengineering and food production, although there are proposals for using fertilized ocean regions for enhanced fish production.

A spatial pattern of the flux is also defined, in the file:

```
biogem_force_flux_ocn_PO4_SUR.dat
```

Again, an example pattern has been set – here, the Equatorial Atlantic. In choosing your regions(s), think about where in the ocean (again – there may be differences between real ocean and model) productivity is currently limited by PO₄. Also be aware of possible on-set of Fe limitation if you relieve the PO₄ limitation (i.e., you could potentially lose effectiveness if you supply too much PO₄ and instead productivity and CO₂ drawdown is capped by a second factor). You could potentially consider PO₄ and Fe addition at the same time ... ?

There is some literature on macro-nutrient addition to the ocean. This often focuses on nitrate (NO₃) rather than PO₄, but you can treat them as effectively interchangeable, i.e. we could have set the model up with NO₃ instead of PO₄ as the sole potentially limiting macro-nutrient in the ocean and your results and conclusions would effectively be the same.

- **Enhanced weathering** (worjh2_FeMahowald2006_FpCO2_Fp13CO2_A2_02180PgC_FALK) (alkalinity addition)

A constant (with time) flux of alkalinity is specified in:

biogem_force_flux_ocn_ALK_sig.dat. The magnitude of the applied flux is then scaled in the *user-config* by the setting:

```
bg_par_ocn_force_scale_val_12=5.0e+13
```

Again, another example total flux. In choosing a total flux to apply, points of comparison include whatever the total weathering flux (via rivers) of alkalinity (often described in terms of the bicarbonate ion flux) to the global ocean is. Also: global cement (lime) production. (Note that in one mole of lime: CaO, you have 2 moles of alkalinity (Ca²⁺).)

A spatial pattern of the flux is also defined, in the file:

```
biogem_force_flux_ocn_ALK_SUR.dat
```

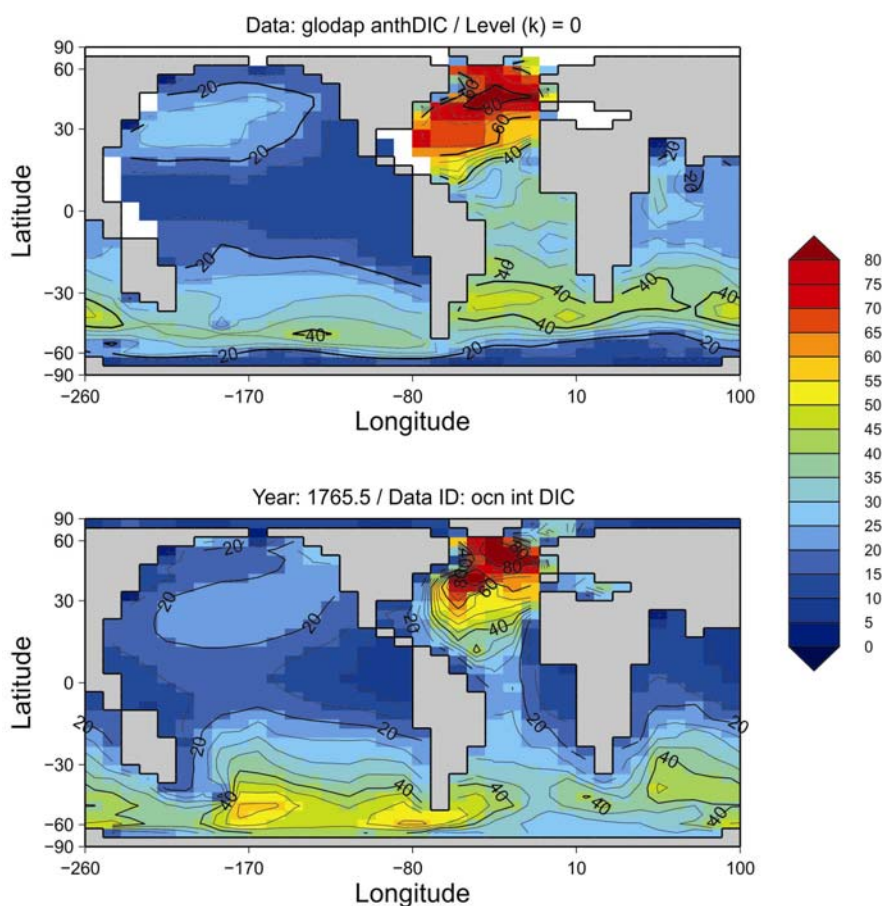
Again, an example pattern has been set – here, bordering the major tropical coral reefs locations in the Western Pacific. In choosing your regions(s), you might think about mitigating specific ecosystem impacts of ocean acidification, or about the feasibility of transport and proximity to abundant limestone (CaCO₃ – the source of lime) and/or energy.

There is little literature on liming the ocean. It is sometimes called 'enhanced weathering' or 'artificial weathering'.

- A.6 The spatial patterns of an applied flux *forcing* to the ocean can easily be modified. The pattern is specified in a simple ASCII (plain text) file, in the file in the forcing sub-directory ending '_SUR.dat'. The file (here for the default Fe pattern) looks like:

some of the high end CO₂ emissions scenarios, there may be a degree of collapse of the AMOC that will presumably affect the patterns of ocean acidification).

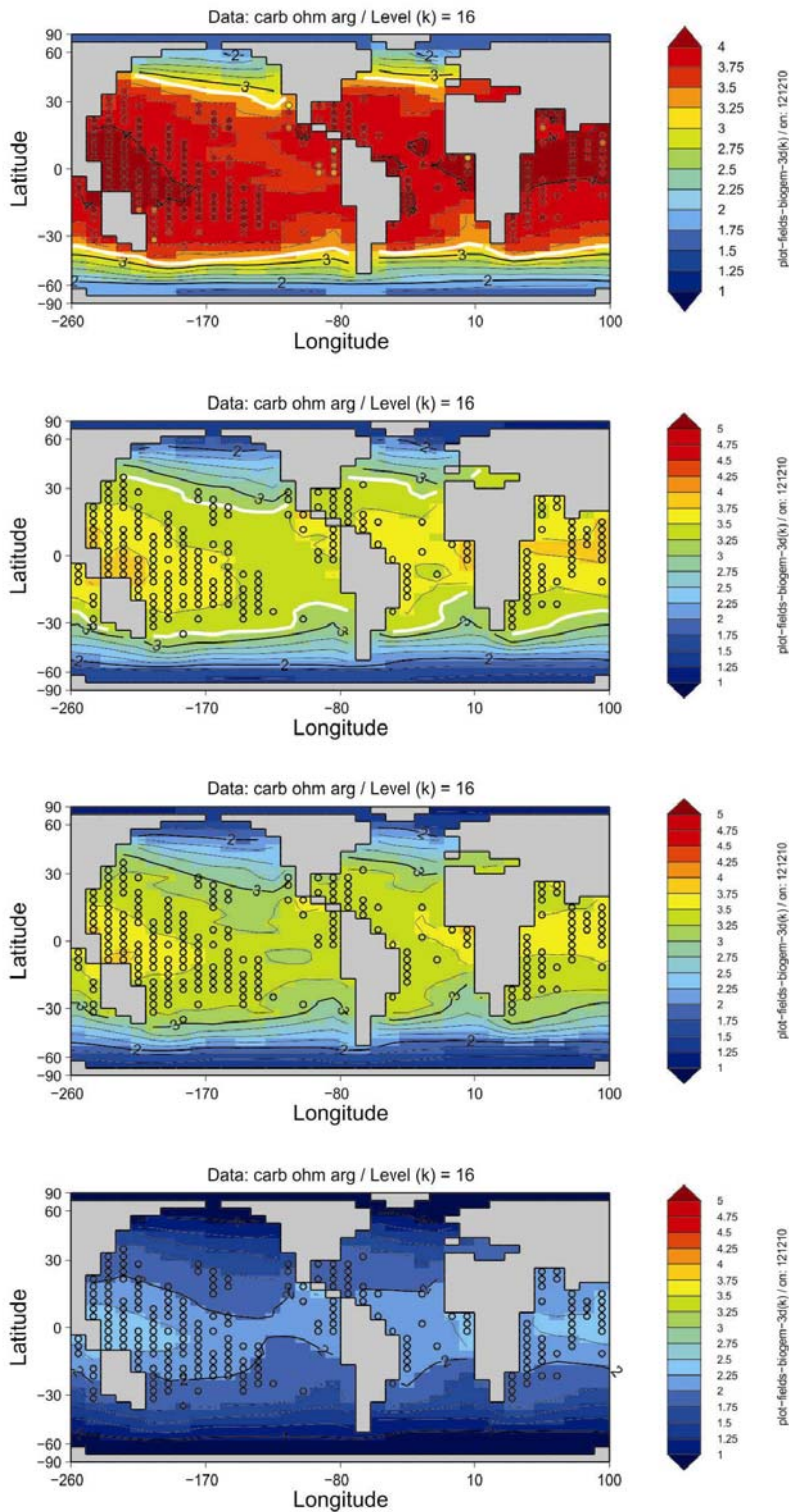
- If you are having doubts that your geoengineering experiment is actually ‘doing’ anything – remember to create anomaly maps (plots) to look for specific changes in e.g. saturation state, pH, or the water column inventory of anthropogenic CO₂. Even before this – plot anomalies of the flux you think you have applied, looking specifically at the region you think you have applied it to. For this, cGENIE saves the 3D distributions of dissolved Fe, PO₄, and ALK (alkalinity).
- Don’t forget to provide a summary description of the model in your paper. Also: think carefully and provide appropriate assessment and/or critical discussion and caveats regarding the model – how much does it differ from the ‘real world’ for the modern ocean, particularly in terms of patterns of carbonate saturation? Does it simulate anthropogenic CO₂ uptake adequately (e.g. see below)?



Observed (top) vs. Model (bottom) anthropogenic CO₂ inventories.

Data and model water column integrals in units of mol CO₂ m⁻² and are nominally with respect to year 1994.

A.8 Examples – here produced using MATLAB (plotting scripts are located in `genie-matlab`) but equally do-able in Panoply (except for the data overlay). (Coral reef location data available upon request.) These are provided simply to illustrate some of the impacts you might consider and possible ways of visualizing them.



Mean annual ocean surface saturation (aragonite) changes.

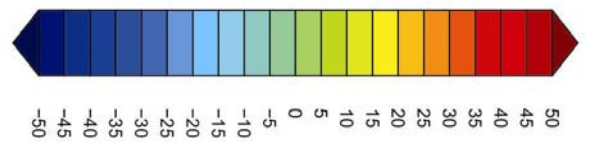
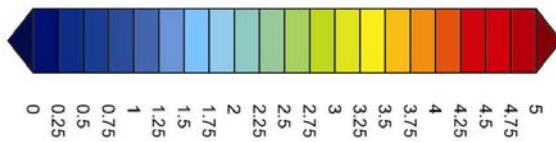
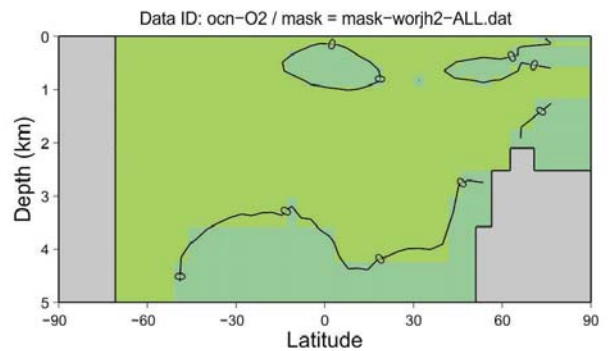
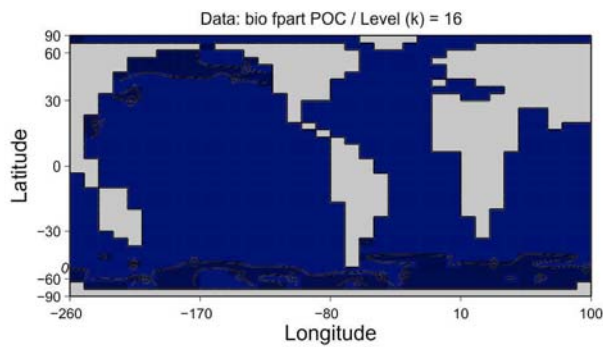
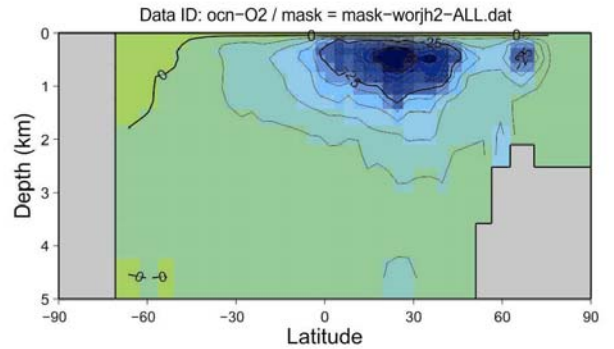
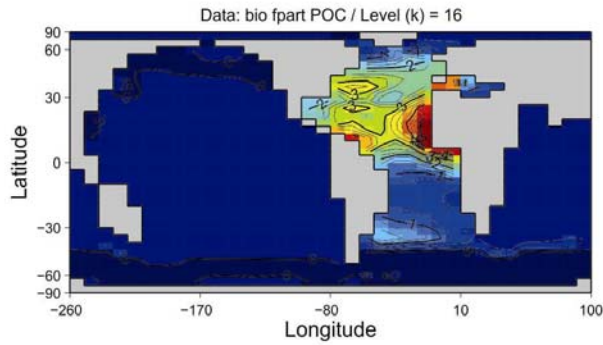
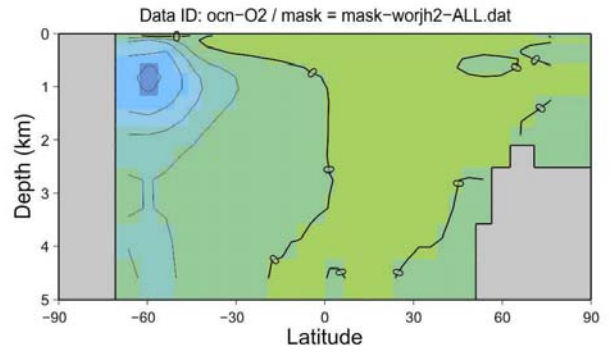
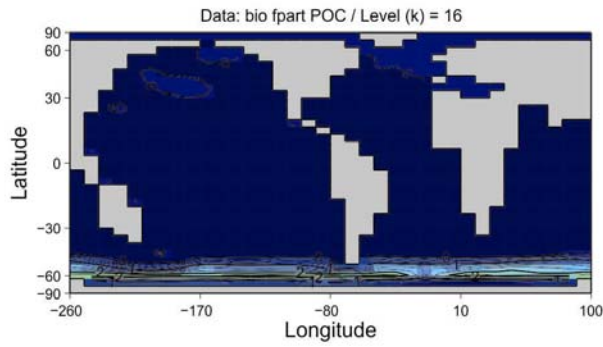
Top: pre-industrial model ocean surface saturation (aragonite) with ReefBase tropical coral reef locations re-gridded to the GENIE grid and color-coded with modern observationally-based saturation values.

2nd down: Year 1994 ocean surface saturation (aragonite) with ReefBase reef locations.

3rd down: Year 2010 ocean surface saturation (aragonite) with ReefBase reef locations.

Bottom: Year 2010 ocean surface saturation (aragonite) under the A2 CO₂ emissions scenario.

The thick white line delineates the 3.25 saturation contour (inferred to reflect a limitation on corals).



Ocean surface export (particulate organic carbon) and zonal [O₂] anomalies.

Left: anomalies of global mean annual export production, for Fe fertilization (top), PO₄ addition (middle), and ocean liming (bottom).

Right: Zonal mean anomalies of dissolved O₂ concentrations.